AD 747482

AFCRL-72-0369
5 JUNE 1972
AIR FORCE SURVEYS IN GEOPHYSICS, NO. 242

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES

L. G. HANSCOM FIELD, BEDFORD, MASSACHUSETTS

Extremes of Hydrometeors at Altitude for MIL-STD-210B

NORMAN SISSENWINE

Approved for public release; distribution unlimited.

AIR FORCE SYSTEMS COMMAND

United States Air Force

26

Qualified requestors may obtain additional copies from the Defense Documentation Center. All others should apply to the National Technical Information Service.

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Air Force Cambridge Research Laboratories (LKI) L. G. Hanscom Field Bedford, Massachusetts 01730	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

EXTREMES OF HYDROMETEORS AT ALTITUDE FOR MIL-STD-210B

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Scientific. Report.

5. AUTHOR(S) *(First name, middle initial, last name)*

Norman Sissenwine

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
5 June 1972	24	25

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) AFCRL-72-0369
b. PROJECT, TASK, WORK UNIT NOS. 8624-01-01	
c. DOD ELEMENT 62101F	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* AFSG No. 242
d. DOD SUBELEMENT 681000	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES TECH, OTHER	12. SPONSORING MILITARY ACTIVITY Air Force Cambridge Research Laboratories (LKI) L.G. Hanscom Field Bedford, Massachusetts 01730

13. ABSTRACT Extremes of precipitation aloft—which would be exceeded with only 0.5 percent probability in the rainy tropics during the rainiest months—are mandatory for design of military equipment that must operate at altitude any place in the world. Also needed are greatest extremes at altitude which should be considered in design when equipment failure, during encounters of improbable intensities, would endanger human life. Frequency distributions of such rainfall intensities and the associated liquid water content in the precipitation and clouds are not available in the climatic inventory.

By extrapolating upward, there are developed nearly instantaneous surface precipitation intensities with appropriate probabilities, utilizing available research data, four models, and tabulations of water content aloft. The maximum mandatory precipitation rate aloft is 1.08 mm/min at 4 to 6 km. Associated water density in the precipitation and clouds totals about 5.5 grams/cm^3. When life is endangered, however, values associated with the world record 1-min rainfall, nearly 50 times this great, are a goal. Other goals, when design for this very improbable world record is not feasible, are included. Complete findings are presented in a single table which includes intensities, liquid water content of precipitation, and liquid water content of cloud particles for nine levels up to 18 km for storms applicable to MIL-STD-210B design philosophy.

DD FORM 1 NOV 65 1473

Unclassified

Security Classification

1a

Unclassified

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Military standard						
Design criteria						
Hydrometeors						
Precipitation						

Unclassified

Security Classification

AFCRL-72-0369
5 JUNE 1972
AIR FORCE SURVEYS IN GEOPHYSICS, NO. 242

AERONOMY LABORATORY PROJECT 8624

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES

L. G. HANSCOM FIELD, BEDFORD, MASSACHUSETTS

Extremes of Hydrometeors at Altitude for MIL-STD-210B

NORMAN SISSENWINE

AIR FORCE SYSTEMS COMMAND
United States Air Force

11

Abstract

Extremes of precipitation aloft—which would be exceeded with only 5 percent probability in the rainy tropics during the rainiest months—are mandatory for design of military equipment that must operate at altitude any place in the world. Also needed are greatest extremes at altitude which should be considered in design when equipment failure, during encounters of improbable intensities, would endanger human life. Frequency distributions of such rainfall intensities and the associated liquid water content in the precipitation and clouds are not available in the climatic inventory.

By extrapolating upward, there are developed nearly instantaneous surface precipitation intensities with appropriate probabilities, utilizing available research data, four models, and tabulations of water content aloft. The maximum mandatory precipitation rate aloft is 1.08 mm/min at 4 to 6 km. Associated water density in the precipitation and clouds totals about 5.5 grams/cm^3. When life is endangered, however, values associated with the world record 1-min rainfall, nearly 50 times this great, are a goal. Other goals, when design for this very improbable world record is not feasible, are included. Complete findings are presented in a single table which includes intensities, liquid water content of precipitation, and liquid water content of cloud particles for nine levels up to 18 km for storms applicable to MIL-STD-210B design philosophy.

Contents

Tables

Preceding page blank

Extremes of Hydrometeors at Altitude for MIL-STD-210B

1. INTRODUCTION

Preparation of MIL-STD-210B, "Climatic Extremes for Military Equipment," a revision of MIL-STD-210A of the same title was directed by the office of the Assistant Secretary of Defense (Installations and Logistics) on 31 January 1969. The administrative responsibility for this revision was assigned to the Commander, Electronic Systems Division (AFSC) with technical responsibility to AFCRL.

Logical extremes of all meteorological elements that could have an impact on design of military equipment are to be included. Of a special importance is the intensity of precipitation at the surface, and the intensity and quantity of precipitation and associated cloudiness at altitude.

The MIL-STD-210B is being divided into three parts: (1) extremes for land operations, (2) extremes for maritime (sea surface and coastal) operations, and (3) extremes for air operations. Precipitation intensities for land operation have been studied and extremes recommended in a special report (Salmela et al, 1971), a supporting background document for this endeavor. The preparers of this surface precipitation material are climatologists who were able to infer short-period intensity precipitation pertinent to military design from the very large inventory of surface weather data. The basic use of these data has applications in

(Received for publication 2 June 1972)

agriculture and hydrology. Such an inventory of data is not available at altitudes applicable to most air operations.

Scientists most knowledgeable about water content in clouds and precipitation aloft have not been able to undertake specification of the extremes for specified calculated risks aloft, since there is not a sufficiently strong scientific inventory of data to argue for the validity of such models. On the other hand, intensive precipitation can make inoperable and even destroy many aerospace systems or equipments. Therefore, design and test have, over the past (Department of Defense, 1967), and are presently (draft revised MIL-STD-810C, "Environmental Test Methods" dated 15 December 1972) specifying extremes with far less scientific support than necessary. Their most recent value of 12 in. in 5 min in this draft (61 mm/min) is double the world-record 1-min rainfall (Riordan, 1970). In view of the urgent need, the author, a climatologist who has the overall responsibility for the scientific realism of MIL-STD-210B, will attempt herein to develop as close an approximation of the models desired as possible. Extrapolation of surface climatological intensities with known probabilities, and recorded extremes to altitude is attempted, utilizing the research information available from meteorologists specializing in cloud physics and radar meteorology.

Many of the extremes being provided in MIL-STD-210B will be useful in design, but yet not generally critical. An example of such an element could be extreme density at a given altitude. For most flight equipment, encountering a condition even greater than the extreme considered logical in design would result in an operation less satisfactory than desired but would not be catastrophic. This is probably not true for extremes of hydrometeors at altitude. The extremes of water content, liquid and ice particles in clouds and precipitation, ingested into a jet engine could create excessive cooling due to vaporization in the intake air compression chambers, causing flameout and a consequent crash. Another family of problems involves triggering of impact fuses of artillery shells and aircraft bombs; still another, erosion of supersonic aircraft radomes and leading edges; finally, ablation of reentry vehicles.

Guidance from the Joint Chiefs of Staff (1969) indicates that military equipment intended for world-wide operations should be designed so that inoperability due to precipitation extremes is probably only 0.5 percent of the time during the worst month in the severest general rainy areas, the very extensive moist tropics. The Joint Chiefs of Staff also state "when inoperability of an item of equipment directly endangers human life, the design criteria for climatic equipment should be established so as to result in a percentage of inoperability which is as close to zero as is practicably possible. The climatic design requirements should be determined on a case by case basis to insure the achievement of maximum practical reliability."

2. GENERAL

Routine observations of precipitation intensity (and associated water content) at altitude are not made. Therefore, frequency distributions of such observations over locations of greatest severity, needed to describe extreme storms pertinent to MIL-STD-210B calculated risk design philosophy, are not available. Some values have been estimated from weather radar research, and a few from aircraft penetration observations. Unfortunately, it is difficult to relate these to the distribution of values over rainy tropics needed to obtain intensities equal or exceeded 0.5 percent of the time in the rainiest months or to the extreme closest to having a zero occurrence probability, design values mandatory for operation of equipment (Joint Chiefs of Staff, 1969). Much of the work of prominent U.S. radar meteorologists has been summarized in the precipitation chapters of AFCRL's handbooks (USAF, 1960 and 1965) and a chapter revision (Cole et al, 1969).

A most recent applied climatology contribution in this field was provided by Briggs (1972). He uses hourly and 2-min surface point rain rates, probabilities of radar echoes aloft, and a sophisticated statistical treatment to relate point rain intensities to severest "instantaneous" intensity applicable in aircraft design, taking aircraft speed into account. He provided alternative curves (for two tropopause heights) of precipitation intensity and liquid water content versus altitude for Heathrow, England; Freetown, S. L.; and Singapore. These curves give the extreme intensity likely in 10^5 flying hours by altitude from 2 (or 3) km to 18 km. Values for Freetown, high tropopause, his most severe model, are provided in the columns under "Briggs 10^5 hr" in Table 1. The surface and 1.5 km intensities were obtained by extrapolating downward from 2 km. Ratios in the third column are of the intensity at altitude relative to that at the surface (6.7 mm/min).

3. "INSTANTANEOUS" INTENSITY ?

The duration of so-called "instantaneous" intensity rain must be considered when evaluating related extreme intensities. Briggs' (1972) doesn't define instantaneous nor how he obtains these intensities from 2-min totals. The surface level value of 6.7 mm/min is 22 percent of the intensity for the highest known recorded surface intensity for 1 min, 31.2 mm, observed from an intense thunderstorm at Unionville, Maryland on 4 July 1956, a thoroughly investigated phenomenon (Riordan, 1970). The previous world record for 1 min was 17.6 mm; the record before that was 16.5 mm (Riordan, 1970), both in the United States. Over a 42-min period at Holt, Missouri on 22 June 1947, 12 in. of rain was recorded. The average intensity of 7.3 mm/min is in fairly close agreement with Briggs' 6.7 mm/min value.

Table 1. Background for Precipitation Extremes at Altitude

Altitude (km)	Briggs 10^5 hr			10^{-6} Montreal			Lake Charles
	(mm/min)	(g/m^3)	ratio	(mm/min)	(g/m^3)	ratio	ratio
Surface	6.7	20	1.00	6.7	14.0	1.00	1.00
1.5	7.7	24	1.15	6.7	14.0	1.00	1.00
3	8.7	27	1.30	6.7	14.0	1.00	1.00
4.5	9.3	29	1.39	6.3	12.1	0.95	0.99
6	9.0	28	1.34	8.3	17.1	1.35	0.96
9	8.0	24	1.20	4.0	5.6	0.60	0.75
12	6.3	18	0.94	0.6	1.5	0.39	0.44
15	3.6	11	0.54	0.15	0.23	0.004	0.19
18	1.0	3	0.15	0.003	0.0045	0.905	0.03

These few values are extracted from decades of records from hundreds of locations and so have extremely low probabilities. It is quite likely that values as great or nearly as great occur in the very rainy tropics more frequently than in the U.S.A., but were not measured and so do not appear in the records. It is unlikely, however, that 1-min precipitation rates from storms elsewhere will greatly exceed rates measured in the U.S.A. since it is the world center of intense precipitating thunder and hail storms which occasionally reach tornado maturity. This statement is borne out by an envelope curve of world record rainstorms over durations of minutes to hours included in the AFCRL handbooks (USAF, 1960 and 1965). The probability of these record intensities are extremely low, much less than the 0.5 percent worst month risk intensity in the rainiest tropics of 0.80 mm/min, being considered as mandatory for surface operations of military equipment (Salmela et al, 1971). However, such improbable extremes must be considered as a preliminary goal in aircraft design since an encounter would endanger life. They may be far from attainable design criteria.

A rigorous definition for instantaneous intensity of precipitation is difficult since it requires a measured amount falling in a finite time. For short time intervals, terminal velocity of drops will become a factor in the usual weighing rain gage techniques. Intensities computed from radar echoes would appear to most nearly provide instantaneous values. They are based upon radar returns at a given instant but due to the beam width, the signal is averaged over a volume which has an areal extent such that the measurement is not for a point as are surface observations.

Fortunately this discrepancy should not be great for the many radar observations taken at reasonably short ranges. At a typical beamwidth of one degree, a volume under observation located 50 nm away, slant distance, will have a diameter of only 1.6 km. In actuality the discrepancy of radar observations averaged over such a diameter, when compared to a point observation averaged over 1 min (high resolution for weighing rain gages), should not be great. In 1 min, a typical convective storm would move about half the distance of the beamwidth if advection is 20 to 30 knots so that the point 1-min measurement is equivalent to the truly instantaneous rate averaged over a path length of about 1/2 to 3/4 km. Discrepancies will be greater for radar observations at greater range but hopefully the mass of high intensity data will be within close range of the radar since for observations at great distance, the high intensities will be smoothed out by the greater volume included in the echo.

Dyer (Cole et al, 1969), in a revision of the weather radar portion of AFCRL's handbooks (USAF, 1960 and 1965), graphically presents the distribution of precipitation intensities in Montreal summer storms. A peak intensity of 6.7 mm/min at the ground is attained. This value had a probability of 10^{-6} based on all storms in one summer. Intensities of 10-6 probability for altitudes are also listed in Table 1 under "10^{-6} Montreal."

Donaldson (1971) recently reviewed radar echoes with intense rainfall. He notes that from theoretical considerations Kessler (1969) "finds a peak rainfall rate of 300 mm/hr (5.0 mm/min) in an intense convective cell where the moisture supply is adequate and thermal structure can support intense updrafts." This rate is lower than the peak intensity in the 10^{-6} Montreal summer storms (8.3 mm/min). An even higher radar determined intensity, 10.8 mm/min, was also noted (Wilson, 1966). It is greater than any other radar intensity in the literature reviewed.

Donaldson (1971) also quotes some applicable non-radar observed extremes. In a special effort to obtain instantaneous rainfall intensities at the surface, Mueller (1966) with a photographic technique which averaged intensity for 10.5 sec, observed most heavy rainfalls over Miami, Florida during a year. Miami has nearly the greatest frequency of thunderstorm activity in the U.S.A. About 1 percent of the Mueller's 10.5-sec intensities measured exceeded 3 mm/min. High resolution weighing rain gage 1-min observations for the same location operating the entire year showed this intensity had a 10^{-5} probability of occurring (5 times in the year) in the annual frequency distributions. It was prepared by the University of Illinois for AFCRL use in statistical modelling of rainfall intensities (Lenhard, et al, 1971). Mueller had one 10.5-sec observation with an intensity equivalent to 12 mm/min. The 1-min sampling weighing rain gage operating at the same location and time observed a maximum of 3.56 mm/min; this had a probability of 2×10^{-6} (roughly 1 min/yr). This large difference with the 12 mm/min cannot be readily explained. (That the value is so much greater than the 1 percent frequency of 3 mm/min makes it suspect.) The fact that the weighing gage measurements are for "clock minute" (consecutive even 1-min intervals) or that the rate determined over a 10.5-sec interval did not continue for a full minute could account for only part of the discrepancy. An earlier data reduction of the weighing rain records in which 30-sec resolution was attempted listed an 11.2 mm/min intensity in part of a minute during this storm, but the record was later edited and this extreme filtered out as being within the noise level of measurement. The maximum 1-min rain gage measurement that has passed careful University of Illinois editing was 5.45 mm/min for Bogor, Indonesia.

In another effort, to understand short duration rates, Hogg (1968) utilized a high speed recorder which enables rainfall intensity changes over seconds to be recorded. He presents 38 min of record during an intense thunderstorm over New Jersey. There are three separate rain bursts of 1, 2-, and 4-min durations during which intensities attained rates equivalent to 4 to 5 mm/min. The 4-min burst was composed of three separate peaks. Durations and magnitudes of intensities during these bursts were estimated with the aid of dividers and a magnifying glass.

During the first burst, the average over the most intense 1-min interval was about 3.4 mm/min. The peak, lasting about 20 sec was 4.4 mm/min. For the second burst, the highest 1-min average was 4.0 mm/min. It included a 30-sec maximum of 4.4 mm/min and a 10-sec peak of 4.5 mm/min. The third burst had two very sharp peaks and a sharp lull in the center of the maximum 1-min average of 3.8 mm/min. (The third peak was outside this 1-min maximum and less intense.) The two peaks, lasting about 3 and 12 sec, had rates equivalent to 4.3 and 4.4 mm/min.

The averaged maximum 1-min intensities of the 3 bursts was 3.9 mm/min. Average intensity of the four peaks was 4.4 mm/min, and average duration 11 sec. From these few high resolution observations, it appears that maximum 1-min averaged intensities are roughly 90 percent of maximums 10 sec averaged intensities.

Summarizing, most examples of extreme intensities presented above indicate that intensities averaged over a minute at the surface at a point are comparable to more nearly instantaneous maximum intensities obtained by radar which averages over volumes having horizontal extents of a couple of kilometers. Evidence also suggests that 10-sec intensities at least 10 percent greater than 1-min intensities will occur at a point during maximum 1-min averaged intensities. Only the Miami 10.5-sec intensity of 12 mm/min, 3 to 4 times the 1-min rate fails to support this evidence. Hershfield (1972), in an attempt to derive extreme-value 1-min rainfall from longer duration observations found that extreme 1-min intensities are only about 1.5 the extreme 5-min intensities. A lesser ratio than 1.5 seems logical for the relationship of 10-sec to 1-min maximum intensities since intense rain shaft must have some maximum diameter. This would support the value of 1.1 suggested by the Hogg (1968) data instead of the factor of 3 to 4 times the 1-min intensity indicated by the anomalous Miami 10.5-sec value.

4. EXTREMES

Briggs' encounter of 6.7 mm/min once in 10^5 hr, year round flying near the surface over Freetown, S. L. (average annual rainfall, 4050 mm), will from the above review of duration, be considered to apply to a 1-min averaged intensity or happen once in 6×10^6 min, a probability of 1.7×10^{-7}. Since there are 525,600 min in a year, it can be deduced that an encounter should be expected about once in 11.4 years over a single location typical of Freetown.

Briggs' surface intensity is about the same as the 10^{-6} Montreal summer storm intensity, a much less rainy area. The 10^{-6} probability, however, is applicable to 1500 storm hours when the intensity at some point in a 20,000 nm^2 area was at least 0.1 mm/min. Thus the probability, over a year, assuming the 10^{-6} intensity is not attained over the colder months, would be 1500/8760 of 10^{-6} or 1.7×10^{-7}, the same as the Briggs' probability. It applies, however, to a core in which intensity is a maximum somewhere within a 20,000 nm^2 area around Montreal, whereas for Briggs it applies to any single location.

For a further check on the general representativeness of these maximum intensity values, they were compared to extremes in the cumulative frequency distributions of actual 1-min intensities for the several locations available in University of Illinois data used by Lenhard et al (1971) to develop models for estimating 1-min rainfall rates. As noted n discussions of the duration of "instantaneous," for Bogor, Indonesia (average annual rain 3250 mm), one of the rainiest of these, a maximum 1-min intensity of 5.45 mm/min was observed. The rain gage was operated only when rain was expected, 147,837 min. (This is less than a third of the year, and so the data could not be used in the AFCRL models for obtaining instantaneous intensities from standard precipitation climatology.) Though some rainfall was probably missed by this procedure, the maximum value of 5.45 mm/min was most likely the maximum for the year. A once in 11.4 yr extreme of 6.7 mm/min, the intensity deduced for Freetown from Briggs' report, is certainly conceivable for Bogor, assuming the available observations are representative, even though the average annual rainfall for Bogor is 80 percent that of Freetown.

For Freetown the 0.5 and 0.1 percent extremes for the rainiest month from Lenhard et al's (1971) regression models are 0.69 and 1.60 mm/min, fairly close to the generalized values of 0.80 and 1.60 mm/min for Burma-Malaysia, the more extensive rainiest tropics (Salmela et al, 1971). Annual rainfall for the Burma-Malaysia area averages about 5300 mm, somewhat higher than Freetown. The severest location, Cherrapunji, India, where the average annual total is 11,400 mm, has a 0.1 percent worst month intensity of 3.13 mm/min (Salmela et al, 1971).

In summary it appears that Briggs' extreme rainfall for Freetown agrees reasonably well with extremes that could be inferred for other very rainy tropics with the probability of about the magnitude suggested by Briggs. This probability, however, is not applicable to current MIL-STD-210B design philosophy for standardized military equipment (a rate equal or exceeded 0.5 percent of the time in the rainiest tropics during the rainiest months).

5. LIQUID WATER CONTENT

Briggs (1972) also presents the liquid water content for various rainfall intensities on the graph summarizing his findings. These have been tabulated in Table 1. The basis for these values is not provided by Briggs. They appear to be derived from the relationship, $M = 0.05\,R$, where M is the mass in g/m^3 and R the intensity in mm/hr (instead of minutes). This is the relationship suggested for the liquid water content from early thunderstorm research and has been suggested in the AFCRL handbooks (USAF, 1960 and 1965). Liquid water contents for the 10^{-6} Montreal summer storm, also in Table 1, are less than half the Briggs' values though the rainfall intensities are nearly the same below 9 km.

Recently, Dyer (Cole et al, 1969) revised the material on precipitation in the latest AFCRL handbook (USAF, 1965). A review of aircraft (F-100 fighter) observed values of liquid water content from 22 passes through six Great Plains thunderstorms above 27,000 ft (7.6 km) reveals only one value exceeding 13.9 g/m^3 (Roys and Kessler, 1966). These measurements include vapor, cloud, and precipitation water. The vapor must have been well below 1 g/m^3 because temperatures were below -30°C and so is considered negligible. Cloud water, however, must be considered.

For these aircraft observations, the conditional probability of the maximum water content in a midwest thunderstorm was found to fit the expression:

$$P(MX) = \exp(-X^2/64),$$

where M and X are in g/m^3. This yields a 0.01 conditional probability (1 percent) value of about 17 g/m^3. Dyer (Cole et al, 1969) note that isolated reports of 30 g/m^3 are mentioned in the Russian literature (Sulakvelidze et al, 1965). This intensity has a 10^{-6} conditional probability using the above expression for Great Plains thunderstorms. This would be equivalent to an unconditional probability of about 10^{-8}, assuming 90 thunderstorm hours for the annual average of 55 thunderstorm days, typical for the area. Briggs' maximum of 29 g/m^3 at 4.5 km for Freetown like tropical areas with a probability of encounter of 1.7×10^{-7}, six times as often as encounters of 30 g/m^3 over the Great Plains is in logical agreement with it. The extreme aircraft measured intensity was 44 g/m^3 (Roys and Kessler, 1966). This has a Great Plains probability of 10^{-12} using the above equation.

An envelope curve of radar data on rain intensity and concurrent water mass on log-log graph paper was developed from data inventory studied by Dyer (Cole et al, 1969). The envelope extremes indicate paired data lie between lines depicting a linear relationship between the logarithm of liquid water content and logarithm of rainfall rate for intensities up to 1.7 mm/min (100 mm/hr) and liquid water contents up to 10 g/m^3. This envelope on 1 cycle log-log paper was extrapolated over a second cycle to provide liquid water contents corresponding to intensities as high as indicated in Table 1. Values obtained from the envelope for these high intensities were compared to liquid water contents in Table 1 and found to be much lower. The intensity of 6.7 mm/min (400 mm/hr) using the envelope yielded only about 10 g/m^3. The maximum value for Briggs' storm from the envelope is only about 12 g/m^3; for Montreal, it is less than 11 g/m^3. These values were taken from the center of the envelope, but using the extremes of the envelope could not provide values approaching those shown in Table 1 or the 30 g/m^3 noted above for Oklahoma thunderstorms. In fact, the 17 g/m^3 value having a 1 percent probability in Great Plains thunderstorms using the envelope would be associated with an intensity aloft of nearly 12 mm/min (700 mm/hr). Though intensity at the surface would only be about 75 percent of this value, such intensities over this area are so infrequent that extrapolation of the relationship beyond the limits provided by Dyer is questionable.

Roys and Kessler (1966) in their review of liquid water content noted that Mueller and Sims (1963-64) had obtained 29 g/m^3 at the surface as a maximum 1-min average for Miami, utilizing raindrop cameras.

The problem was reviewed with R. Dyer, author of the precipitation data in the revised handbook chapter (Cole et al, 1969). Extrapolation of the envelope to higher values of intensity was not intended. Atlas (1964) gives three possible relationships between intensity and in a survey of radar meteorology:

$$M = 0.072R^{0.88} \tag{1}$$

$$M = 0.070R^{0.83} \tag{2}$$

$$M = 0.052R^{0.97} \tag{3}$$

where M is precipitation content (g/m^3) and R is intensity (mm/hr).

Equation (1), often termed the Marshall-Palmer expression, is a generalized relationship for all types of storms but it is not tailored for the extreme convective storms of most concern in engineering design. It is the expression used for the Montreal 10^{-6} storm in Table 1. Equation (2) differs little from Eq. (1); it originated in India and is intended to be applicable to thunderstorms in that area. Equation (3) originated in Illinois and is specifically applicable to intense thunderstorms. It differs only slightly from the simple linear expression apparently utilized for the "Briggs 10^5 hr" in Table 1:

$$M = 0.05R \tag{4}$$

A tabulation of liquid water contents obtained from these expressions is given in Table 2.

Table 2. Liquid Water Contents

R		M(g/m^3)			
(mm/hr)	(mm/min)	Eq. (1)	Eq. (2)	Eq. (3)	Eq. (4)
1	0.02	0.07	0.07	0.05	0.05
10	0.17	0.54	0.47	0.48	0.50
30	0.50	1.44	1.18	1.40	1.50
50	0.83	2.25	1.80	2.31	2.50
100	1.67	4.14	3.20	4.53	5.00
150	2.50	5.92	4.48	6.71	7.50
200	3.33	7.62	5.69	8.87	10.00
250	4.17	9.28	6.84	11.01	12.50
300	5.00	10.89	7.96	13.14	15.00
400	6.66	14.03	10.11	17.38	20.00
500	8.33	17.08	12.17	21.58	25.00
600	10.00	20.05	14.16	25.75	30.00
700	11.67	22.96	16.09	29.90	35.00

Obviously, only Eqs. (3) and (4) can provide precipitation content for extreme intensities that are in agreement with values observed by aircraft penetrations and logical to expect for very very improbable intense storms. With Eqs. (1) and (2) values of up to 14 g/m^3, previously indicated as quite ordinary in Great Plains thunderstorms, would be associated with intensities of several mm/min, not very ordinary over the Great Plains, indicating that these relationships are not applicable. No doubt better relationships between intensity and liquid water content will be found by researchers specializing in this meteorological area, but Eq. (3) will be used herein as that available for providing liquid water content during extreme convective precipitation which is supported best in the scientific literature.

The water content intended above is that of the precipitation size drops to which storm radar are sensitive. At altitude the largest drops will be falling, whereas smaller sizes may be supported by the upward convection currents since they have lower terminal velocities. However, an aircraft flying through these rain areas above the base of the clouds, about 1 km, will not discriminate between upward or downward moving precipitation and will also be ingesting cloud particles. The aircraft measurements of water content in the Great Plains thunderstorms were made in jet engine compression chamber. That values are much higher than available from radar, Eqs. (1) and (2), could possibly be due to this additional smaller cloud particle water. Electromagnetic radiation of radar wavelengths used in most storm radars is reflected only by drops of precipitation size.

A sharp demarcation in size between raindrops, a conglomeration of cloud particles which have appreciable terminal velocity, and cloud particles is difficult. Cloud particles cover a spectrum of sizes from several to tens of microns. Raindrops range from fractions of a millimeter up to several millimeters. The official manual for weather radar observations (U.S. Dept. Commerce, 1967) gives 100 microns as the size of precipitation drops generally detectable on C, S, and X band weather radars. This value will be used in distinguishing between the density of cloud and precipitation in the material that follows. The specific distributions of cloud and precipitation sizes depend on intensities of cloudiness and precipitation. They will not be covered in this report.

Aircraft penetrations of convective clouds to measure cloud water mass are reported in the precipitation chapters of the AFCRL handbooks (USAF, 1960 and 1965; Cole et al, 1969). For cumulonimbus and cumulus congestus clouds, maximum water content of 10 g/m^3 at 3.5 km was observed. That value, however, was suspected of being contaminated by raindrops. The highest value unquestionably composed only of cloud particles was about 6.5 g/m^3. The average cloud water contents in cumulus congestus and cumulonimbus are 2 and 2.5 g/m^3. A theoretical curve of liquid water content in a rising air parcel with a 20°C surface dew point yields a maximum of 7 g/m^3 at about 5 or 6 km, but the observed average value of 2.5 g/m^3 appears to hold from about 1.5 km up to the maximum height of observations, 6 km. The average cloud water content 2.5 g/m^3 will be added to the values for precipitation aloft for the least intensive model of convective precipitation being developed and extrapolated upward to 10 g/m^3 for more intense models.

A problem that has been ignored is the physical state of this precipitation, liquid or solid. Supercooled liquid can be found far below the freezing temperature in convective clouds but -40°C is the usual minimum. The typical freezing altitude in areas and periods of extreme convection is 4.5 km. A temperature of -40°C is found at about 10 km. Precipitation should be considered all liquid below 4.5 km, and a mixture of water and ice becoming ice with increasing altitude to all ice above 10 km. There will also be much hail throughout the intense convective cloud, but hail encounters for MIL-STD-210B is provided in a separate study (Gringorten, 1972). However, the relationship between liquid water content and precipitation rates based upon radar echoes becomes quite tenuous, since the echoes strength reflected from ice for a given intensity precipitation can differ considerably from echoes from pure liquid precipitation and this is difficult to take into account.

6. VERTICAL EXTENT

Briggs' (1972) rain intensity increases with altitude to a maximum at 4.5 km decreasing above this level to a light rain at 18 km, the maximum altitude. Ratios of intensity aloft to those at the surface are shown in Table 1. Though 18 km is generally above the height of the highest tropopause, a lid to most convective activity, Kantor and Grantham (1968) have found precipitation echoes above this level 1 percent of the time along the Mississippi Valley in July, supporting Briggs' extension to above 18 km.

The "10^{-6} Montreal" probability distributions tabulation shows a rainfall intensity minimum between the surface and the altitude of maximum intensity at 4 to 6 km, the level of maximum rain storage just above the freezing level. The minimum between the surface and this altitude is quite slight in the "Montreal 10^{-6}" intensity profile.

A major intensity maximum just above the freezing level at 4 to 6 km is logical on the basis of highest vertical convective forces storing and accumulating many rain drops at that level. A minimum of intensity between the surface and this level could certainly be found at any instant during a mature thunderstorm activity, because of the sporadic bursts of rain which at moments of greatest intensity at surface level may have momentarily slowed aloft. However, a minimum between the altitude of maximum intensity and the surface in a generalized vertical distribution of intensity with altitude is difficult to understand. It implies a second maximum level of rain production near the convective condensation level, the base of the clouds. Such a distribution also shows up in an example of a moderate shower over Montreal, presented by Dyer (Cole et al, 1969). The maximum intensity of 0.4 mm/min at 9 km decreases to less than 0.1 mm/min at 6 km and increases to greater than 0.1 mm/min below 5 km. Donaldson in discussion indicates that ground clutter or handling of the radar reflectivity data may be responsible, and advises that such a minimum not appear in a model of strong convective precipitation.

In arriving at profiles of very severe rain storms for MIL-STD-210B, it seems reasonable to accept an increase of intensity from the surface to 4 to 6 km of about 35 percent as shown by the Briggs and Montreal extreme precipitation intensity profiles in Table 1. The wide range of ratio of intensity at altitudes above this maximum to intensity at the surface leads to a need for further investigation.

Reference has been made to a three year study (Kantor and Grantham, 1968) of hourly observations of precipitation echoes on 10-cm wavelength storm radars over the United States which support Briggs' extension of his intense precipitation model to 18 km or higher. A companion study (Grantham and Kantor, 1967) provides similar tabulations of precipitation echoes for three years earlier by month, 2-hr periods, and total hours a day for 5000-ft layers from the surface to 70,000 ft (21.3 km). Frequencies (not intensity) of echoes within 100 nm of thirty-one U.S. Weather Bureau WSR-57 (10 cm) storm radars are tabulated. Lake Charles, Louisiana tabulations for July typify the probabilities of heavy convective activity extending precipitation size particles upward from very moist tropical air into the stratosphere. A total of 2005 observations were available for three Julies. For the layer 0 to 5000 ft, echoes were present on 1198 observations, 62.8 percent of the time. Three observations (0.0015 probability) had echoes above 65,000 ft (19.8 km) and one showed precipitation above 70,000 ft (21.4 km). The ratios of frequencies at higher level to those at the lowest level are shown in the column labeled "Lake Charles" in Table 1.

7. SUMMARY

For operation of surface military equipment, rainfall design criteria are rainfall rates equaled or exceeded with a probability of 0.5 percent in the rainiest tropics during the rainiest month (0.8 mm/min). Such a rainfall rate was derived for the surface (and near surface) from long period operational weather records. Distributions of intensity aloft for such a storm are only available by inference from radar for a few isolated meteorological research locations. These distributions are for very limited periods and incomplete.

Also required when "inoperability of equipment will directly endanger human life" is record extremes at altitudes to use as goals so that the "percentage of inoperability is as close to zero as possible" (Joint Chiefs of Staff, 1969). The 0.1 percent probable extreme at the surface for the rainy tropics, 3.13 mm/min, was derived for the station with the greatest rainfall amounts, as an arbitrary very low risk value. However, record storms of 7.3 mm/min intensity lasting 42 min, and 31.2 mm/min lasting 1 min give some idea of truly catastrophic conditions possible. These are provided as preliminary goals, but estimates of probabilities are not possible for these very unlikely events. [The 7.3 mm/min storm is in fairly close agreement with recommendations by Briggs (1972) as a heavy rain likely to be encountered in 10^5 flying hours in the very rainy tropics.]

Table 3 provides the upward extension of these various surface intensities applicable to MIL-STD-210B from ratios provided in the first column. These ratios are a composite of ratios presented in Table 1. The intensity ratios were used for the surface to 6 km and the Lake Charles precipitation echoes from 6 km to higher altitudes. Liquid water content of the precipitation is based upon Eq. (3).

The cloud water was also subject to the same ratios except no clouds were shown for the level below 1.5 km. These can be extrapolated to 1 km, a typical

Table 3. Low Probability Models of Hydrometeors Aloft

Altitude (km)	Ratios		0.5% Worst Month Tropics			0.1% Worst Month Tropics			42-Minute Record			1-Minute Record		
				water			water			water			water	
	prec	cld	rate $\left(\frac{mm}{min}\right)$	prec $\left(\frac{g}{m^3}\right)$	cld $\left(\frac{g}{m^3}\right)$	rate $\left(\frac{mm}{min}\right)$	prec $\left(\frac{g}{m^3}\right)$	cld $\left(\frac{g}{m^3}\right)$	rate $\left(\frac{mm}{min}\right)$	prec $\left(\frac{g}{m^3}\right)$	cld $\left(\frac{g}{m^3}\right)$	rate $\left(\frac{mm}{min}\right)$	prec $\left(\frac{g}{m^3}\right)$	cld $\left(\frac{g}{m^3}\right)$
Surface	1.00	0	0.88	2.22	0	3.13	8.35	0	7.26	18.88	0	31.2	77.65	0
1.5	1.12	0.83	0.90	2.49	2.07	3.50	9.30	8.12	8.15	21.12	8.12	34.9	86.57	8.12
3.0	1.24	0.92	0.99	2.73	2.30	3.88	10.28	9.00	9.02	23.30	9.00	38.7	95.70	9.00
4.5	1.35	1.00	1.08	2.97	2.50	4.23	11.18	9.78	9.82	25.30	9.78	42.1	103.80	9.78
6.0	1.35	1.00	1.08	2.97	2.50	4.23	11.18	9.78	9.82	25.30	9.78	42.1	103.80	9.78
9.0	0.75	0.56	0.60	1.68	1.44	2.35	6.32	5.53	5.44	14.27	5.53	23.5	58.98	5.53
12.0	0.44	0.32	0.35	0.97	0.81	1.38	3.77	3.18	3.19	8.50	3.18	13.8	35.20	3.18
15.0	0.19	0.14	0.15	0.43	0.35	0.59	1.65	1.38	1.38	3.77	1.38	5.94	15.54	1.38
18.0	0.03	0.02	0.02	0.06	0.05	0.09	0.27	0.21	0.22	0.66	0.21	0.84	2.59	0.21

Notes:

1. Intensities are 1-min averages. 10-sec extremes will be 110% of these values.
2. Cloud density is not increased as rain intensity increases beyond the 0.1% model.
3. All liquid below 4.5 km; mostly liquid at 4.5 to 6 km becoming increasingly ice up to 10 km; nearly all ice above 10 km.
4. Cloud particles are less than 100 microns in diameter; precipitation drops more than 100 microns.

cloud base altitude for extreme convection in the tropics. The average cloud droplet water content of 2.5 g/m^3 is shown at the altitude of maximum concentration of the 0.5 percent probable storm. Cloud water contents are proportionately increased for the 0.1 percent storm. Cloud water contents for record storms are assumed the same as for the 0.1 percent storm in accordance with a conversation with R. M. Cunningham, Chief Convective Cloud Physics Branch, AFCRL. Dr. Cunningham believes that the intense precipitation feeds from these clouds at such a rate as to limit the density to not greater than 10 g/m^3.

As an independent check on the values of liquid water derived from radar reflectivity equations in Table 2, the liquid water content of the precipitation near the surface needed to provide the rates of accumulation at the ground was computed. A simple assumption, that most of the accumulation was caused by large drops with terminal velocities of 8 mps, was used. Such a velocity is attained by drops of about 3 mm diameter (Sissenwine and Court, 1951). Liquid water contents thus derived are 75, 78, 80 and 84 percent of the values shown in Table 2 in increasing order of intensity. These percentages support the liquid water contents derived from radar which will include many smaller drops falling at slower velocities.

Acknowledgments

Mrs. Rosemary Dyer and Mr. Ralph Donaldson, Weather Radar Branch, and Dr. R. M. Cunningham, Chief Convective Cloud Physics Branch, provided advice and help for which I am grateful.

References

Atlas, D. (1964) Advances in Radar Meteorology, Vol. 10, Academic Press, New York.

Briggs, J. (1972) Probabilities of aircraft encounters with heavy rain, Met. Mag. 101 (No. 1194):8-13.

Cole, A.E., Donaldson, R.J., Dyer, R., Kantor, A.J., and Skrivanek, R.A. (1969) Precipitation and Clouds, AFCRL-69-0487.

Department of Defense (1967) Military Standard Environmental Test Methods, MIL-STD-810B, Aeronautical Systems Division, Wright-Patterson AFB, Ohio.

Donaldson, R.J., Jr. (1971) Some Examples of Intense Radar Echoes Equivalent to Rainfall Rates in Excess of 2 Inches per Hour, AFCRL RCS-536, unpublished.

Grantham, D.D. and Kantor, A.J. (1967) Distribution of Radar Echoes Over the United States, AFCRL-67-0232.

Gringorten, I.I. (1972) Hailstone Extremes for Design, AFCRL-72-0081, AFSG No. 238.

Gringorten, I.I., Salmela, H.A., Solomon, I. and Sharp, J. (1966) Atmospheric Humidity Atlas-Northern Hemisphere, AFCRL-66-621, AFSG No. 186.

Hershfield, D.M. (1972) Estimating the extreme-value 1-minute rainfall, J. Appl. Met. (in press).

Hogg, D.C. (1968) Millimeter-wave communication through the atmosphere, Science, 159(No. 3810):39-46.

Joint Chiefs of Staff (1969) Views of the Joint Ch fs of Staff regarding the establishment of climatic extremes as mandatory design criteria for standardized military equipment, in Memorandum for the Secretary of Defense, JCSM-502-69, 12 August 1969, Subject: Military Standard MIL-STD-210A, Climatic Extremes for Military Equipment.

Kantor, A.J., and Grantham, D.D. (1968) A Climatology of Very High Altitude Radar Precipitation Echoes, AFCRL-68-0630.

Preceding page blank

Kessler, E. (1969) On the distribution and continuity of water substance in atmospheric circulations, Meteorological Monographs, 10(No. 32).

Lenhard, R.W., Cole, A.E., and Sissenwine, N. (1971) Preliminary Models for Determining Instantaneous Precipitation Intensities from Available Climatology, AFCRL-71-0168, ERP 350.

Mueller, E.A. (1966) Radar Cross Sections from Drop Size Spectra, PhD thesis, U. of Illinois, reprinted in Final Report under Contract DA-28-043 AMC-00032 (E), pp. 12-88.

Mueller, E.A. and Sims, A.L. (1963-64) Liquid Water Content of Rain, Appendix in 9th Technical Report of the Illinois State Water Survey, U.S.A. ERD&L, Contract DA36-039SC87280.

Riordan, P. (1970) Weather Extremes Around the World, TR 70-45-ES, U. S. Army Natick Laboratories, Natick, Mass.

Roys, G.P., and Kessler, E. (1966) Measurements by Aircraft of Condensed Water in Great Plains Thunderstorms, ESSA Tech Note 49-NSSP-19.

Salmela, H.A., Sissenwine, N., and Lenhard, R.W. (1971) Preliminary Atlas of 1.0, 0.5, and 0.1 Percent Precipitation Intensities for Eurasia, AFCRL-71-0527, ERP 374.

Sissenwine, N. and Court, A. (1951) Climatic Extremes for Military Equipment, Dept. of the Army, Office of the Quartermaster General, Report No. 146.

Sulakvelidze, G. K., Bibilashvili, N. Sh., and Lapcheva, V. F. (1965) Formation of precipitation and modification of hail processes, Gidrometeorologicheskoe Izdatel'-stvo, Leningrad, Translation by Israel Program for Science Translations (1967, No. 1808), available from the U.S. Dept. of Commerce.

USAF Geophysics Research Directorate (1960) Surface air temperature probabilities, also precipitation models, Handbook of Geophysics, The MacMillan Co., New York.

USAF Air Force Cambridge Research Laboratories (1965) Precipitation Models, Chapter V, Handbook of Geophysics and Space Environments, McGraw Hill Book Co., Inc., New York.

U.S. Dept. Commerce (1967) Meteorological Radar WSR-57M, ESSA Weather Bureau, Vol. 3, p. 4-1.

Wilson, J.W. (1966) Storm to storm variability in radar reflectivity-rainfall rate relationship, RMC 12:229-233.